Title

The Sudbury Neutrino Observatory and the Solar Neutrino Problem

Authors

Lesko, K.T.
Chan, Y.D.
Garcia, A.
et al.

Publication Date

1993-01-05

LBL-34241
UC-413

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Presented at the Sixteenth Nuclear Physics Symposium,
Oaxtepec, Mexico, January 5–8, 1993, and to be
published in the Proceedings

The Sudbury Neutrino Observatory and the Solar Neutrino Problem

K.T. Lesko for the Collaboration

January 1993

NUCLEAR SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

DISCLAIMER

LBL - 34241

The Sudbury Neutrino Observatory and the Solar Neutrino Problem

K. T. Lesko for the Collaboration

Nuclear Science Division, Lawrence Berkeley Laboratory
University of California, Berkeley, California 94720, USA

January 1993

This work was supported by the Director, Office of Energy Research Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098

THE SUDBURY NEUTRINO OBSERVATORY AND THE SOLAR NEUTRINO PROBLEM

K.T. Lesko, Y.D. Chan, A. García, E.B. Norman, A.R. Smith, R.G. Stokstad, I. Žlimen
Nuclear Science Division, Lawrence Berkeley Laboratory
Berkeley, CA 94720, U.S.A.

H.C. Evans, G.T. Ewan, A. Hallin, H.W. Lee, J.R. Leslie, J.D. MacArthur, H.B. Mak, A.B. McDonald, W. McLatchie, B.C. Robertson, P. Skensved, B. Sur
Physics Department, Queen's University
Kingston, Ontario K7L 9N6, Canada

E. Bonvin, E.D. Earle, D. Hepburn, G.M. Milton
AECL Research, Chalk River Laboratories,
Chalk River, Ontario K0J 1J0, Canada

I. Blevis, W.F. Davidson, C.K. Hargrove, H. Mes, M. Shatkay, D. Sinclair
Centre for Research in Particle Physics, Carleton University
Ottawa, Ontario K1S 5B6, Canada

A.L. Carter, B. Hollebone, D. Kessler
Physics Department, Carleton University
Ottawa, Ontario K1S 5B6, Canada

P. Jagam, J. Law, R.W. Ollerhead, J.J. Simpson, J.-X. Wang
Physics Department, University of Guelph
Guelph, Ontario N1G 2W1, Canada

J. Bigu, E.D. Hallman, R.U. Haq, C. Virtue
Physics Department, Laurentian University
Sudbury, Ontario P3E 2C6, Canada

S. Gil, C. Waltham
Physics Department, University of British Columbia
Vancouver, British Columbia V6T 1W5, Canada

M.M. Lowry
Physics Department, Princeton University
Princeton, NJ 08544, U.S.A.

E.W. Beier, W. Frati, M. Newcomer, R. Van Berg
Physics Department, University of Pennsylvania
Philadelphia, PA 19104, U.S.A.

T.J. Bowles, P. Doe, M.M. Fowler, A. Hime, F. McGirt, R.G.H. Robertson, T.C. Spencer, D.J. Vieira, J.B. Wilhemy, J.F. Wilkerson, J.M. Wouters
Physics Division, Los Alamos National Laboratory
Los Alamos, NM 87545, U.S.A.

N.W. Tanner, N.A. Jelley, J.C. Barton, G. Doucas, E.W. Hooper, A.B. Knox, M.E. Moorhead, M. Omori, P.T. Trent, D.L. Wark
Physics Department, University of Oxford
Oxford OX1 3RH, U.K.

1. Solar Neutrino Problem

Four experiments have now reported solar neutrinos measurements . Three of these experiments rely on neutrino capture on large targets producing radioactive species[1,2,3]. These experiments then detect the very small number of subsequent decays. The ^{37}Cl detector has been reporting neutrino fluxes for more than 20 years with increasing precision[1]. The fourth experiment decays neutrino scattering from electrons in a large water-Čerenkov detector[4]. This last experiment is distinguished in that they observe a real-time signal of the neutrino flux and are able to establish a correlation with the sun's position. The details of these experiments are summarized in Table I.

During the last several decades solar models have developed an increasing degree of completeness and complexity[5]. These models are able to predict the spectrum and absolute flux of neutrinos arriving at the earth. They have been used to predict the neutrino flux for all of the above experiments as well as for experiments now being developed. The Standard Solar Model (SSM) predictions for these four experiments are presented in Table I and the ratio of the observed to expected fluxes, taking into account the thresholds for the different reactions.

Experiment	Target	Technique	Threshold (MeV)	SSM Flux on Earth (SNU)	Flux (% SSM)
Homestake Mine	^{37}Cl	$\nu_e + {}^{37}Cl \Rightarrow {}^{37}Ar$ ($t_{1/2}$=35 days)	0.814	7.9 ± 0.1	2.05±0.3 (27%)
SAGE	^{71}Ga	$\nu_e + {}^{71}Ga \Rightarrow {}^{71}Ge$ ($t_{1/2}$=12 days)	0.233	132^{+20}_{-17}	$58^{+17}_{-24} \pm 14$ (44%)
GALLEX	^{71}Ga	$\nu_e + {}^{71}Ga \Rightarrow {}^{71}Ge$ ($t_{1/2}$=12 days)	0.233	132^{+20}_{-17}	83 ± 17 ± 14 (63%)
Kamioka	H_2O	$\nu_e + e^- \Rightarrow \nu_e + e^-$ (elastic scattering)	7.5	-	49 ± 4± 6 %

Table 1. Four experiments which have observed solar neutrinos. The first three experiments rely on "inverse beta-decay" to produce a radioactive species whose subsequent decay is observed. These three experiments integrate the

neutrino flux for periods comparable to the half-life of the capture daughter. The thresholds for all four experiments are presented in column 4. The Standard Solar Model[5] predictions are presented in column 5. Finally, the ratio of the Standard Solar Model predictions to the experimental fluxes[6] are given in column 6. If multiple errors are presented, the first is the statistical error and the second is an estimate of the systematic error.

The Standard Solar Model and these four experiments define the solar neutrino problem: that the best solar models predict a neutrino flux on earth two to four times that which has been reported.

2. Possible Solutions to the Solar Neutrino Problem

A number of different solutions to this problem have been investigated over the past few decades, including vacuum neutrino oscillations, temperature dependence of solar models, and most recently matter-enhanced neutrino oscillations (the so-called MSW effect)[5, 7].

The large suppression of observed neutrino flux on earth, specifically the electron-type neutrino that the above experiments only have sensitivity to, has naturally lead to the speculation that the neutrino favor eigenstates are not also mass eigenstates. And with the correct selection of parameters and mixing some suppression of ν_e could be realized. This possibility is intriguing since it requires that at least one species of neutrino must have non-zero mass. However, in order to obtain adequate suppression of ν_e flux the parameters have to be carefully tuned to specific values, to obtain the "just-so" oscillations. While this presents a possible explanation to the solar neutrino problem it is considered unlikely by many.

The very large temperature dependences of the neutrino flux to solar core temperatures naturally suggest that perhaps the solar models are slightly off in this parameter. The different neutrino sources in the sun have different temperature dependences, presented in Table 2. Using the four different experimental neutrino fluxes with their distinct thresholds allow us to examine the sensitivity of the solar model to reduced core temperatures.

Neutrino Source	Neutrino Energy (MeV)	Temperature Dependence
pp	≤0.420	$T_c^{-1.2}$
^{7}Be	0.861 0.383	T_c^{+8}
^{8}B	≤15.	T_c^{+18}

Table 2. Predicted temperature dependence of the dominate neutrino fluxes observed by the four solar neutrino detectors. The neutrino energies (spectra) and temperature dependence are given in columns 2 and 3 (reference 5).

While individually the experiments yield reduced core temperatures which match the observed neutrino flux, taken together the different temperature dependences and different thresholds can not be well fit with a single reduced T_C. So the most obvious correction to the solar model is strongly disfavored by the sum of all the neutrino flux data[7].

The final potential solution to the solar neutrino problem to be considered here is matter enhanced oscillations or the MSW effect[8]. This particular mechanism is attractive because it singles out the ν_e for reduction. This effect is named for Wolfenstein, Mikheyev and Smirnov. As in the vacuum oscillation case, it is assumed that the initial state vector for the neutrino is a superposition of flavor (e, μ, τ) eigenstates. The time evolution of the state vector is determined by both a vacuum mass matrix and a contribution due to the presence of matter. This term has its origin in the electroweak model and is due to the exchange of both neutral and charged current intermediate bosons (W or Z). The neutral current scattering is approximately equal for all flavors of neutrinos and effectively adds a constant to the mass matrix. The charged current term (the exchange of a W^+ between a neutrino and an electron in the surrounding media) is responsible for the selection of the electron-neutrino suppression. This term represents the contribution to the neutrino index of refraction of electron-neutrino scattering. Varying density distributions of electrons will produce spatially varying indices of refraction and, consequently, suppression of electron-type neutrinos.

The results of matter-oscillations are usually represented as contours of constant flux (rate) for the different experiments as a function of two variables: Δm^2 is the mass difference between two oscillating neutrino states and a trigonometric function of Θ_V, the vacuum mixing angle. The latter is usually $\sin^2 2\Theta_V$ or $\sin^2 2\Theta_V/\cos 2\Theta_V$.

In Δm^2 - $\sin^2 2\Theta_V/\cos 2\Theta_V$ space the equal rate contours form triangles. The first leg is defined by a resonance condition where most of the high-energy neutrinos are suppressed. This condition applies for $\Delta m^2 \sim 10^{-4}$ eV^2 for $0.0002 < \sin^2 2\Theta_V/\cos 2\Theta_V < 2$. The second leg is defined by large angle-mixing and results in nearly uniform suppression for all neutrinos. This condition apples for $10^{-7} < \Delta m^2 < 10^{-4}$ eV^2 and $\sin^2 2\Theta_V/\cos 2\Theta_V \sim 2$. In this region day-night effects could be observed due to regeneration of neutrinos due to the mass of the earth, when the earth is between the sun and the experiment. The final leg of the triangle which joins ($\Delta m^2 \sim 10^{-4}$ eV^2, $\sin^2 2\Theta_V/\cos 2\Theta_V \sim 0.0002$) to ($\Delta m^2 \sim 10^{-7}$eV^2, $\sin^2 2\Theta_V/\cos 2\Theta_V \sim 2$) is known as the non-adiabatic solution. In this solution, neutrinos emitted for the core of the sun experience rapidly varying matter densities and the neutrino states jumps between eigenstates, in analogy to nearly degenerate level crossings. This solution presents energy dependent neutrino suppression.

Combining the observed neutrino fluxes for the four experiments defines two allowed regions in Δm^2 - $\sin^2 2\Theta_V/\cos 2\Theta_V$ space: one along the non-adiabatic solution at ($\Delta m^2 \sim 10^{-5}$ eV^2, $\sin^2 2\Theta_V/\cos 2\Theta_V \sim 10^{-2}$) and the other along the large-angle solution at ($\Delta m^2 \sim 10^{-5}$ eV^2, $\sin^2 2\Theta_V/\cos 2\Theta_V \sim 2$). The existing experiments are unable to distinguish between these two solutions and we must await new experiments to obtain a better handle on the experiment.

3. The Sudbury Neutrino Observatory

The rest of this paper will describe the Sudbury Neutrino Observatory (SNO). SNO will provide the information necessary to decide which of these solutions to the "solar neutrino problem" is correct.

The Sudbury Neutrino Observatory will consist of a 1000 tonne heavy water (D_2O) Čerenkov detector that is designed to measure the flux, energy spectrum, and direction of neutrinos from the Sun and from such other sources as supernovae. It is presently under construction in a very low background environment 2000 meters underground in the Creighton mine near Sudbury, Ontario, Canada. This is an operating nickel mine owned by INCO, Ltd. The D_2O used in the detector will be on loan from Atomic Energy of Canada Limited.

The basic measurements that will be made with the SNO detector are:

1) the flux and energy spectrum of electron-type neutrinos reaching the Earth, and

2) the total flux of all neutrino types above an energy of 2.2 MeV.

With these two measurements, it will be possible to :

1) determine if neutrino oscillations occur, and

2) independently test solar models by determining the production rate of high energy electron-type neutrinos in the solar core.

The SNO detector utilizes three complementary neutrino interactions with the heavy water.

1) The neutrino-electron elastic scattering (ES) reaction: $\nu_x + e^- \rightarrow \nu_x + e^-$.

The observed signal in the detector is the Čerenkov light produced by the recoiling electron. This is the primary detection mechanism for light water detectors such as the Kamioka detector. It is sensitive to all neutrino types, but is dominated by the electron neutrino. The recoiling electrons from the ES reaction are strongly forward peaked and give excellent directional information. However, information about the energy spectrum of the neutrinos is more difficult to extract because of averaging over the outgoing neutrinos.

2) The charged current (CC) reaction: $\nu_e + d \rightarrow p + p + e^-$ (Q = -1.44 MeV).

This reaction of the electron-type neutrino on the deuteron is unique to the SNO detector. It has a relatively large cross section for ^8B neutrinos and would produce about 10 events per day for one third of the SSM flux. This is greater than fifty times more sensitive than existing solar neutrino experiments. The electron energy is $E_e = E_\nu - 1.44$ MeV and the energy resolution is approximately 20%. This reaction gives good spectral information on the ^8B neutrinos and thus provides good sensitivity to the MSW effect. This reaction will also identify electron neutrinos from the initial burst of a supernova.

3) The neutral current (NC) reaction: $\nu_x + d \rightarrow \nu_x' + p + n$ (Q = -2.2 MeV).

This reaction can be observed by the detection of the gamma rays resulting from the subsequent neutron capture or by a neutron detector array in the heavy water. This reaction is sensitive to all types of neutrinos equally and would be used to measure the total flux of neutrinos above the threshold energy of 2.2 MeV. The expected counting rate for the full SSM is approximately 10 per day. This will give a direct measure of the total solar ^{8}B neutrino production independent of neutrino oscillation effects. It will also detect all types of neutrinos from supernovae explosions.

The D_2O target of the SNO detector will be contained in a transparent spherical acrylic vessel with a diameter of 12 m and a wall thickness of 5 cm. Approximately 2.5 m outside the acrylic vessel, there will be about 9600 photomultipliers (PMTs) with 20-cm diameters uniformly arranged and held in place by a geodesic support structure. A reflector is mounted in front of each PMT to increase the light collection to yield a total effective photocathode coverage of approximately 60%. The PMT array is sensitive to Čerenkov radiation produced by relativistic electrons and other particles in the central regions of the detector. The acrylic vessel, PMTs, and the support structure are immersed in 7300 tonnes of ultrapure H_2O. This reduces the background in the heavy water from radioactive impurities in the rock walls and in the detector components. The cavity which will house the detector is barrel shaped with a diameter of 22 m and a height of 30 m. The excavation of the cavity is expected to be completed early in 1993. The PMT support structure and acrylic vessel will then be assembled and installed underground. The initial water fill is scheduled to begin near the end of 1994, with a view toward completing commissioning tests and starting to take data in 1995. The data taking sequence that will be used in the experiment is still under discussion. It may begin with a H_2O fill of the acrylic vessel followed by a D_2O fill. The NC measurement may then be made either by adding 2.5 tonnes of NaCl to the D_2O (in order to raise the energy of the capture gamma rays) or through the use of discrete neutron detectors (such as ^{3}He counters) installed in the D_2O.

References

1. R. Davis, Jr. *et al.*, Phys. Rev. Lett. **20** (1968) 1205, J.K.Rowley *et al.*, in *Solar Neutrinos and Astronomy*, eds. M. L. Cherry, W. A. Fowler, and K. Lande (AIP, New York, 1985).

2. A. Abuzov *et al.*, Phys. Rev. Lett. **67** (1991) 3332.

3. P. Anselmann *et al.*, Phys. Lett. **B285** (1992) 376.

4. K. Hirata *et al.*, Phys. Rev. Lett. **65** (1990) 1297.

5. J. N. Bahcall, *Neutrino Astrophysics* (Cambridge Univ. Press, Cambridge, 1989), J.N. Bahcall and M.H. Pinsonneault Rev. Mod. Phys. **64**, 885 (1992)

6. Recent experimental results for the SAGE and GALLEX experiments were reported at the 16th Texas Symposium of Relativistic Astrophysics and 3rd Symposium of Particle, Strings, and Cosmology held at the University of California, Berkeley, December, 1992.

7. S.A. Bludman, N. Hata, D.C. Kennedy, and P.G. Langacker, University of Pennsylvania preprint 1992.

8. L. Wolfenstein, Phys. Rev. D, **17**, 2369 (1978), L. Wolfenstein, Phys. Rev. D, **20**, 2634 (1979), S.P. Mikheyev and A.Yu. Smirnov Sov. J. Nucl. Phys., **42**, 913 (1986), S.P. Mikheyev and A.Yu. Smirnov *Nuovo Cimento*, **9C**, 17 (1986), and H.A. Bethe, Phys. Rev. Lett., **56**, 1306 (1986)

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720